MicroLEIS DSS:
For Planning Agro-Ecological Soil Use and Management Systems

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ABSTRACT

The main focus of this chapter is that using soil type information in decision making is at the heart for sustainable use and management of agricultural land. The MicroLEIS decision support system (DSS) is based on the multifunctional evaluation of biophysical soil quality, using basically input data collected in standard soil inventories, and with particular reference to the peculiarities of the Mediterranean region. Its design philosophy is a toolkit approach, integrating many software instruments: databases, statistic models, expert systems, neural networks, Web and GIS applications, and other information technologies. As a case study applying MicroLEIS DSS to Cordoba Province (Spain), soil specific strategies to maximize land productivity and to prevent land degradation are predicted within two major topics: i) strategies related to land use planning at a regional scale, and ii) strategies related to soil management planning at a farm level. This DSS has proved to be an appropriate methodology for converting knowledge on land use and management systems, as estimated by research scientists, into information that is readily comprehensible to policy makers and farmers.

INTRODUCTION

To develop a new and truly sustainable agriculture that reverses environmental deterioration and at the same time augmenting the supply of food, agro-ecological innovations are necessary which consider the importance of using soil information in decision-making (Ball & De la Rosa, 2006). Soils can be used for almost all agricultural purposes if sufficient inputs are supplied. The application of inputs can be such that they dominate the conditions in which crops are grown, as can be the case in greenhouse cultivation. However, each soil unit has its own potentialities and limitations, and each soil use its own biophysical requirements. External inputs or improvements are expressed in

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terms of capital, energy, or environmental costs. A main aim of sustainable agriculture is to minimize these socio-economic and environmental costs by predicting the inherent capacity of a soil unit to support a specific soil use and management for a long period of time without deterioration. Sustainable soil use and management must sustain biophysical soil potentiality and, at the same time, diversify the agricultural soil system, considering all the possible options to increase crop production: i) expansion of the agricultural land surface; ii) introduction of improved crop varieties; iii) use of irrigation techniques; iv) application of fertilizers and pesticides; and v) rationalization of soil tillage practices (Robert et al., 1993). In brief, in the design of sustainable agro-ecosystems, the challenge for the near future will be to increase the crop production on less land, and with less labor, water and pesticides.

Agro-ecological innovations are based on similar scientific principles considered by FAO in its Agro-ecological Zoning Project (AEZ; FAO, 1978) which was a milestone in the history of land evaluation. Technical guides for implementing agro-ecological approaches must be prepared in considerable detail, and localized so that they apply specifically to the soil type for which they are intended. In this way, research information produced by academic, government, and private organizations must be consistently compiled, evaluated, and formatted for use by specialists and lay people (Arnold, 2004). As the best example, the Electronic Field Office Technical Guides (eFOTG; USDA, 2004) are the primary scientific references for the US Natural Resources Conservation Service. They contain specific information about the use and conservation of soil and related resources. Appropriate parts of the eFOTG are automated as databases, computer programs, and other electronic-based elements, in order to make recommendations more site-specific. In Europe, it is now beginning to see the start of a proactive approach to soil protection strategies to promote sustainable land use and management (Stoate et al., 2001). For example, in 2002 the Commission of the European Communities issued a Communication entitled "Towards a Thematic Strategy for Soil Protection" (CEC, 2002). This was a first step towards an integrated strategy on the issue at the European level, and was followed in 2004 by the European Strategy for Soil Protection (CEC, 2004).

The new concept of soil quality as "the capacity of a specific kind of soil to function with its surroundings, sustain plant and animal productivity, maintain or enhance soil, water and air quality and support human health and habitation" (Karlen et al., 1997), based on data collected in standard soil surveys, appears to be the most appropriate framework. The soil physical, chemical, and biological quality is of manifest importance in achieving sustainable agricultural systems, which balance productivity and environmental protection. Although soil biological quality indicators are not considered in land evaluation, this agro-ecological approach can be a useful procedure for analyzing the soil physical and chemical quality from the viewpoint of long-term changes (Ball & De la Rosa, 2006).

Emerging technology in data and knowledge engineering provides excellent possibilities in land evaluation development and application processes. The application phase of land evaluation systems is a process of scaling-up from the representative areas of the development phase to implementation in unknown scenarios. The application phase–previously accomplished manually–can now be executed with computer-assisted procedures. This involves the development and linkage of integrated databases, computer programs, and spatialization tools, constituting decision support systems (De la Rosa & Van Diepen, 2002).

Decision support systems are computerized technology that can be used to support complex decision-making and problem-solving (Shim et al., 2002). Opinions are wide-ranging as to what constitutes a decision support system. A database management system could arguably be used as a decision support system for certain applications. Many people consider geographic information systems very useful decision support systems (Booty et al., 2001). Classic decision support system design comprises of components for i) sophisticated database management capabilities with access to internal and external data, information, and knowledge, ii) powerful modeling functions accessed by a model management system, and iii) simple user interface designs that enable interactive queries, reporting, and graphing functions (Shim et al., 2002).

In this chapter, the approaches used and experience gained in the development of the *MicroLEIS DSS* project are discussed. Emphasis is given to the achievements made in passing from a land evaluation system to a land resources information system, and in the beginnings of a land evaluation decision support system. Also, examples of applying *MicroLEIS DSS* in selected application areas of Cordoba province, Southern Spain, are presented and discussed in this chapter. Concrete measures to combat soil degradation on agricultural lands, with special reference to the Mediterranean region, are analyzed within two major topics: i) land use planning at a regional level, and ii) soil management recommendations at a farm level. With this case study is intended to show the possibilities of using an agro-ecological land evaluation decision support system, such as *MicroLEIS DSS*, to draw up site-specific sustainable agricultural practices.

THE MICROLEIS DSS

The evolution of the *MicroLEIS* (Mediterranean Land Evaluation Information System) follows the three eras of growth in the computer industry: i) the data processing era, ii) the microcomputer era, and iii) the network era. During the first era, some qualitative and statistical land evaluation models were developed. The first microcomputer-based results were in the DOS environment in the early 1990s (De la Rosa et al., 1992), and then moved to WINDOWS in the late 1990s. Since 1998, the *MicroLEIS* system has also been considered well-suited to take advantage of the opportunities that the Internet presents, especially the rapid dissemination of information and knowledge, making the system more efficient and more widely used.

The *MicroLEIS DSS* system was developed to assist specific types of decision-makers faced with specific agro-ecological problems. It has been designed as a knowledge-based approach which incorporates a set of information tools, as illustrated in Figure 1. Each of these tools is directly linked to another, and custom applications can be carried out on a wide range of problems related to land productivity and land degradation. They are grouped into the following main modules: i) environmental data warehousing, ii) agro-ecological land evaluation modeling, and iii) application user-interface. The architecture is open in design.

Environmental Data Warehousing

Data warehousing can be greatly facilitated if the nearly infinite list of basic data are systematically arranged and stored in an ordered format for ready sorting and retrieval. Database management systems are responsible for these tasks and consist of attribute tables manipulated by relational database management systems, and a geometric component handled by geographical information systems (GIS).

The land attributes used in MicroLEIS DSS correspond to the following three main factors: soil/site, climate, and crop/management (Table 1). Soil surveys are the building blocks of the comprehensive data set needed to drive land evaluation. Because climatic conditions vary from year to year, reliable long-term data are used to reflect the historical reality and to predict future events with some degree of confidence. Traditionally, agricultural management aspects have been considered a prerequisite only in land

Figure 1. Conceptual design of the MicroLEIS land evaluation decision support system, including database management capabilities, modeling functions and interactive user interface (Source: Updated from De la Rosa et al. (2004). With permission)

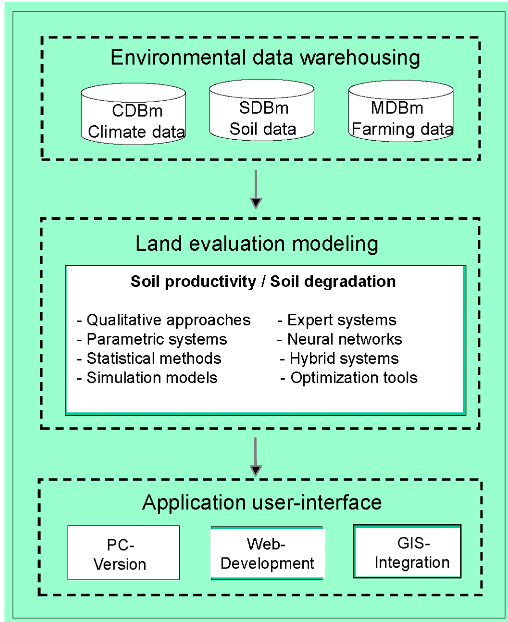


Table 1. Set of input land characteristics considered in the MicroLEIS DSS models, although not all the variables are needed for each model.

Factor type	Input land characteristic
	Land productivity modeling
Site/Soil	Latitude, Altitude, Physiographic position, Parent material, Slope gradient, Useful depth, Stoniness, Texture, Clay content, Structure, Color, Reaction, Organic matter content, Carbonate content, Salinity, Sodium saturation, Cation exchange capacity, Free iron, Bulk density, Drainage, Water retention, Hydraulic conductivity.
Climate	Monthly precipitation, Monthly maximum temperature, Monthly minimum temperature.
Crop/Management	Growing season length, Maximum rooting depth, Specific leaf area, Crop coefficient, Coefficient of efficiency.
	Land degradation modeling
Site/Soil	Latitude, Altitude, Physiographic position, Parent material, Slope gradient, Slope form, Slope aspect, Land cover, Useful depth, Stoniness, Texture, Clay content, Structure, Organic matter content, Carbonate content, Salinity, Sodium saturation, Cation exchange capacity, Bulk density, Drainage, Water retention, Hydraulic conductivity
Climate	Monthly precipitation, Monthly maximum precipitation, Monthly maximum temperature, Monthly minimum temperature.
Crop/Management	Land use type, Growing season length, Leaf situation, Leaf duration, Plant height, Maximum rooting depth, Sowing date, Tillage practice, Tillage depth, Row spacing, Artificial drainage, Conservation technique, Residues treatment, Crop rotation, Operation sequence, Implement type, Material input type, Material input rate, Wheel load, Tire inflation pressure.

evaluation. Today, management factors are being incorporated as input variables in response to a growing need for integrating farming information.

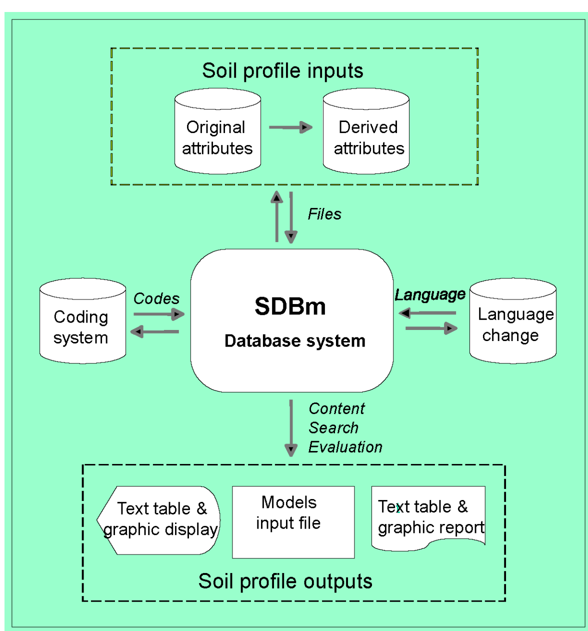
For each of these main factors, a relational database has been constructed: *SDBm*, *CDBm,* and *MDBm*, with inter-connectivity between the three databases. This development of a relational database management system to facilitate the integrated use of land attributes has been critical in decision support.

Soil Database

The multilingual soil database *SDBm* (De la Rosa et al., 2002) is a geo-referenced soil attribute database for storage of an exceptionally large number of morphological, physical, and chemical soil profile data. This database is the "engine" of the *MicroLEIS DSS* system. It is user-friendly software designed to store and retrieve efficiently and systematically the geo-referenced soil attribute data collected in soil surveys and laboratories (Figure 2). The database has the following main characteristics: i) running on WINDOWS platforms; ii) 'help menus' facilitating data entry; iii) automatic translation from English to Spanish, French, and German; iv) metadata feature to describe the methods used in laboratory analysis; v) temporal mode to collect over time the analytical, physical, and hydraulic soil properties; vi) structured query procedure to allow detailed searches; vii) simple graphical analyses and report generation; and viii) a input file generator for the automatic transfer of the stored soil attribute data to GIS and computerized land evaluation models.

The *SDBm* database is considered an essential part of any support system for the exploration in decision-making for sustainable agriculture development. However, this sophisticated database can be useful for independent storage of primary soils information assembled at regional or national level, or for temporary storage of data

Figure 2. The multilingual soil database SDBm scheme, for ready storage, sorting and retrieval of geo-referenced soil profile attributes (Source: Adapted from De la Rosa et al. (2002). With permission)



accumulated during a particular soil survey or monitoring exercise at local level.

Climate Database

The climate database *CDBm* developed for *MicroLEIS DSS* is a computer-based tool for the organization, storage, and manipulation of agro-climatic data for land evaluation. These geo-referenced climate observations, at a particular meteorological station, correspond to the mean values of such records for a determinate period. It is precisely by a period of time that meteorology is distinguished from climate. The basic data of *CDBm* are the mean values of the daily dataset for a particular month. The stored mean monthly values correspond to a set of temperature and precipitation variables (maximum temperature, minimum temperature, accumulative precipitation, maximum precipitation per day, and days of precipitation).

The *CDBm* database includes the following main features: i) a menu-based interactive user interface; ii) extensive, powerful search facilities; iii) options for import/export of basic data; iv) a set of subroutines for calculating climate variables for use in land evaluation (various types of potential evapotranspiration, humidity index, aridity index, growing season length, precipitation concentration index, erosivity index, and leaching degree); v) a generator of daily temperature data from the monthly data; and vi) an option to make a climate summary for each meteorological station for a period of years or a particular year, with graphic representation.

Farming Database

The farming database *MDBm* is knowledge-based software to capture, store, process, and transfer agricultural crop and management information obtained through interviews with farmers. Each *MDBm* dataset consists of geo-referenced agricultural information on a particular land use system. This structured collection of information is stored as a database file. A menu system guides the user through a sequence of options to capture the management practices followed on a site-specific farm. Input parameters are farm and plot descriptions, crop characteristics, sequence of operations, and behavioral observations. These parameters represent a total of 59 default variables according to good management practices on Mediterranean farms. The variables can be modified or extended as appropriate. All the default generalization levels of the input variables are translated to work in the English, Spanish, French, and German languages.

The *MDBm* database includes the following features: i) a menu-based interactive user interface; ii) extensive, powerful search facilities; iii) a glossary-coding system to maintain the classification and codes of the input variables; iv) options for import/export of basic data; v) an input file generator to link with the evaluation models; and vi) an option to make an agricultural management summary for each farm. Application possibilities of *MDBm* include standard description of farming practices, automatic translation and comparison between different languages, and the fitting of agricultural management to site-specific conditions.

Agro-Ecological Land Evaluation Modelling

In the *MicroLEIS DSS* system, land evaluation analysis focuses on agricultural land use, planning, and management for soil protection purposes. Table 2 shows a list of the *MicroLEIS DSS* models in two sets corresponding to i) land use planning, and ii) soil management planning. This modeling or classification phase is accomplished with basic information from representative areas, while the application or generalization phase is carried out in unknown scenarios.

The modeling phase involves the following main stages:

Table 2. MicroLEIS land evaluation models according to the soil function evaluated and the concrete strategy supported for environmentally sustainable agriculture.

Constituent model	Land evaluation issue (Modelling approach)	Specific strategy supported
Land use planning-related		
Terraza	Bioclimatic deficiency (Parametric)	Quantification of crop water supply and frost risk limitation
Cervatana	General land capability (Qualitative)	Segregation of best agricultural and marginal agricultural lands
Sierra	Forestry land suitability (Qualitative/Neural network)	Restoration of semi-natural habitats in marginal agricultural lands: selection of forest species (61)
Almagra	Agricultural soil suitability (Qualitative)	Diversification of crop rotation in best agricultural lands: for traditional crops (12)
Albero	Agricultural soil productivity (Statistical)	Quantification of crop yield: for wheat, maize, and cotton
Raizal	Soil erosion risk (Expert system)	Identification of vulnerability areas with soil erosion problems
Marisma	Natural soil fertility (Qualitative)	Identification of areas with soil fertility problems and accommodation of fertilizer needs
Soil management planning-related		
ImpelERO	Erosion/impact/mitigation (Expert system/Neural network)	Formulation of management practices: row spacing, residues treatment, operation sequence, number of implements, and implement type
Aljarafe	Soil plasticity and soil workability (Statistical)	Identification of soil workability timing
Alcor	Subsoil compaction and soil trafficability (Statistical)	Site-adjusted soil tillage machinery: implement type, wheel load, and tire inflation
Arenal	General soil contamination (Expert system)	Rationalization of total soil input application
Pantanal	Specific soil contamination (Expert system)	Rationalization of specific soil input application: N and P fertilizers, urban wastes, and pesticides

- *selection* of land attributes: land characteristics and associated land qualities;
- *definition* of relevant land use requirements or limitations: land use response or degradation level;
- *matching* of land attributes with land use requirements: identifying cause-effect relationships through narrative statements,

matching tables, decision trees, response curves, rating indexes, weighting factors, or comprehensive models; and

- *validation* of the developed algorithms in other representative areas.

The selection of land attributes (site/soil, climate, and crop/management factors) as input variables or diagnostic indicators for the predictive models is an essential part of the land evaluation analysis.

The comparison or matching stage forms the basis for assessing the suitability of the land for a particular use. This interpretation process is often difficult and subjective because of a lack of knowledge on the land performance. Current progress in information technology is making possible the application of many different modelling techniques to the most complex systems. The more complicated methods allow the quantitative trend of land evaluation analysis. Models are considered a simplified representation of the real world which can be expressed in a wide variety of forms such as conceptual diagrams, classification systems, and statistical or deterministic mathematical models. In land evaluation, empirical-based modeling has moved on from simple qualitative approaches to others which are more sophisticated and based on artificial intelligence techniques. Additionally, process-based modeling - which is deterministic and based on an understanding of the actual mechanisms - has been incorporated into land evaluation (Van Lanen, 1991). The land evaluation methodology developed in *MicroLEIS DSS* is considered as follows, from least to most sophisticated.

Qualitative Approaches

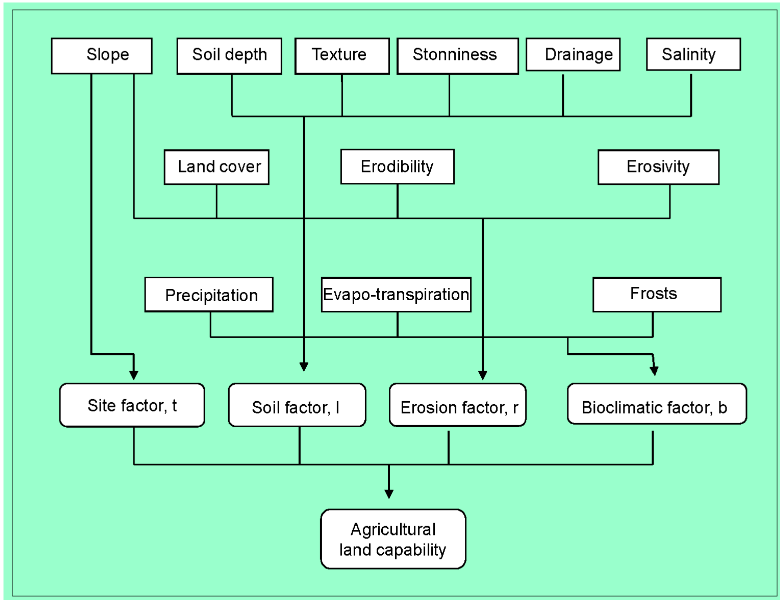
The matching of the land characteristics with land use requirements or limitations may be as simple as narrative statements of land suitability for particular uses, or it may group lands subjectively into a small number of classes or grades of suitability. In many qualitative approaches, a formal quantification is achieved by the application of the rule that the most-limiting land quality determines the degree of land suitability or vulnerability. This assumes knowledge of optimum land conditions and of the consequences of deviations from this optimum (Verheye, 1988). These relatively simple systems of land evaluation depend largely on experience and intuitive judgement: they are real empirical models. No quantitative expressions of either inputs or outputs are normally given. The 'USDA Land Capability System' (1961) and its diverse adaptations (Figure 3), such as typical qualitative land evaluation approaches, have been widely used around the world.

In the initial development of *MicroLEIS DSS*, the qualitative methods of the land user's experience were widely used to predict the general capability for most of the major crops and the specific suitability for a particular crop or selected forest species (i.e. *Cervatana*, *Almagra,* and *Sierra1* models, respectively; De la Rosa et al., 1992). In the *Almagra* approach, simple matching tables are used to express qualitatively soil suitability classes for twelve traditional crops (wheat, corn, melon, potato, soybean, cotton, sunflower, sugar beet, alfalfa, peach, citrus, and olive) according to the principle of maximum limitation factor. The *Marisma* model also uses a qualitative methodology to establish the limitations of a given soil according to selected soil indicators of natural fertility.

Expert Systems

Expert systems, such as artificial intelligence-based techniques, are computer programs that simulate the problem-solving skills of one or more human experts in a given field and provide solutions to a problem. These systems express inferential knowledge by using decision trees. In land evaluation, decision trees give a clear expression of the matching process, comparing land use requirements and land characteristics.

Figure 3. A typical qualitative land classification approach, showing the combination of soil and climate attributes to generate general capability classes. Example: Cervatana model (Source: Updated from De la Rosa et al. (1992). With permission)



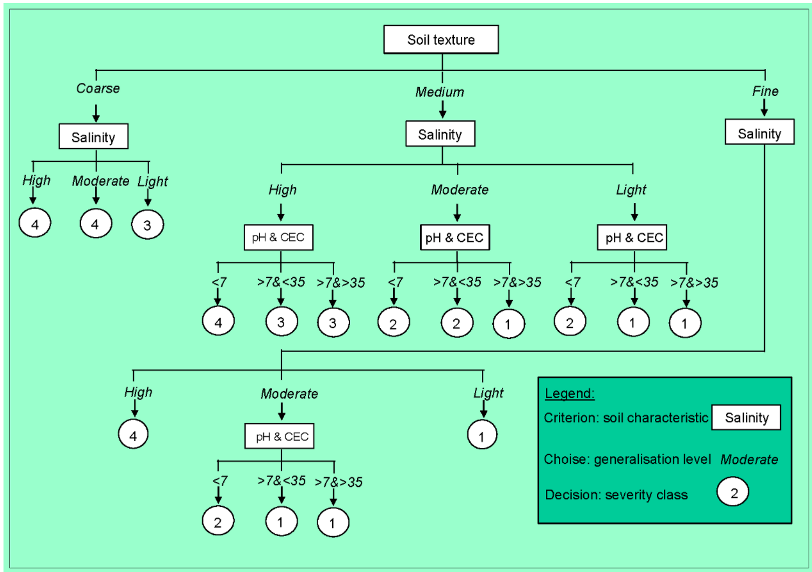
The expert decision trees are based on scientific background (theoretical description) and results of experiences of and discussions with human experts (practical experience), and thereby reflect available expert knowledge.

Decision trees are hierarchical multi-way keys in which the leaves are choices (classes/ranges), such as land characteristic generalization levels, and the interior nodes of the tree are decision criteria, such as land quality severity levels or land suitability classes (Figure 4). Decision trees give a clearer picture of the sequence of decisions being made than do traditional matching tables. Where suitable practical experience data are available, statistical decision tree analysis can be used to generate land evaluation models with good prediction rates when the assumptions for other statistical models are not met. These classification and regression trees are designed to deal with a low ratio of number of observation to number of variables, typical of soil and land resource surveys. This analysis is an iterative process of identifying attributes that are critical in the description of the response variable.

Usually, both expert system procedures–theoretical decision trees and statistical decision trees–are used in order to optimize the results. The Automated Land Evaluation System (ALES; Rossiter, 1990) is a computer program that allows land evaluators to build expert systems for evaluating land units according to the method presented in the FAO Land Evaluation Framework (FAO, 1976). Evaluators can build their own expert system with ALES, taking into account local conditions and objectives. ALES is not an expert system by itself, and does not include any knowledge about land and land use. It is a shell within which evaluators can express their own local knowledge. The selection of land characteristics and associated land qualities for a given land utilization type, which is a crucial activity in land evaluation, is not facilitated by this shell.

The *Arenal*, *Pantanal,* and *Raizal* models of *MicroLEIS DSS* incorporate techniques from

Figure 4. Part of a decision tree model, identifying and combining soil attributes which are critical in the description of the land vulnerability assessment. Example: Arenal model (Source: Adapted from De la Rosa et al. (1993). With permission)



expert system to provide a smattering of support to the decision-makers. These expert knowledge models which consider a reductionist structure predict the land vulnerability risks to general and specific diffuse contamination, and to water erosion, respectively (De la Rosa et al., 1993).

Parametric Systems

Between qualitative and quantitative methods lie semi-quantitative land evaluations, derived from the numerically inferred effects of various land characteristics on the potential behavior of a land use system. Parametric methods can be considered a transitional phase between qualitative methods, based entirely on expert judgment, and mathematical models. They account for interactions between the most-significant factors by simple multiplication or addition of single-factor indexes (Riquier, 1974).

Multiplicative systems assign separate ratings to each of several land characteristics or factors, and then take the product of all factor ratings as the final rating index. These systems have the advantage that any important factor controls the rating. The first and most widely known effort to spell out specific, multiplicative criteria for rating land productivity inductively was developed by Storie (1933). The USLE-type land degradation systems, basically the Universal Soil Loss Equation (USLE; Wischmeier & Smith, 1965) and its adaptations, have a very similar form to that of the Storie index, and are also operated by multiplying the factor values. In the additive systems, various land characteristics are assigned numerical values according to their inferred impact on land use. These numbers are either summed, or subtracted from a maximum rating of 100, to derive a final rating index. Additive systems have the advantage of being able to incorporate information from more land characteristics than multiplicative systems.

Parametric models can also provide quantitative information, especially on the soil water regime and how it affects crop performance. The agro-climatic zoning project (AEZ; FAO, 1978) was a milestone in the history of land evaluation, introducing a new approach to land suitability assessment and sparking the development of quantified methods of land use systems analysis (Driessen and Konijn, 1992).

In the *MicroLEIS DSS* system, as a continuation of the *Almagra* model and prior to the *Albero* model developments, several approaches were developed following multiplicative and additive methodologies, with particular reference to soil suitability for the olive crop (De la Rosa et al., 1992). The *Terraza* model uses a single procedure to simulate the influence of bioclimatic deficiency on a traditional crop, through an adaptation of the AEZ bioclimatic scheme.

Statistical Methods

In land evaluation, statistical systems are powerful empirical methods for predicting land suitability on the basis of selected land characteristics. Correlation and multiple regression analyses have been used to investigate the relative contributions of selected land characteristics on land suitability and land vulnerability. Where suitable basic and response data are available, statistical models can provide the basis for objective ratings of land attributes (Graaff, 1988).

The land suitability/vulnerability or response variable *Y* is analyzed as a function of the type

$$Y = \phi\ (X_1, X_2, \ldots, X_n) + \varepsilon$$

where *Xn* corresponds to the selected land characteristics or independent variables (e.g. soil depth, clay content, organic matter, caption exchange capacity, pH, sodium saturation, etc.), and ε measures the residual. Although the mathematical form of ϕ is not known, this function can often be approximated satisfactorily, within the experimental context, by a polynomial equation. The calibration of this polynomial model can be treated statistically as a particular case of multiple regression. The regression coefficient (R^2) fitted by this analysis represents an inductive validation index of the model corresponding to that accounted for by the percentage of the observed variation.

This methodology has been especially used to predict soil productivity for major crops (Olson and Olson, 1986). Statisticians, agronomists, and soil scientists must work together to develop polynomial regressions to benefit from such statistical analysis. Statistical relationships are also often used to estimate certain engineering or geotechnical properties of soils (e.g. plasticity, workability, and compaction) from pedological characteristics (e.g. clay content, organic matter, and bulk density; De la Rosa, 1979).

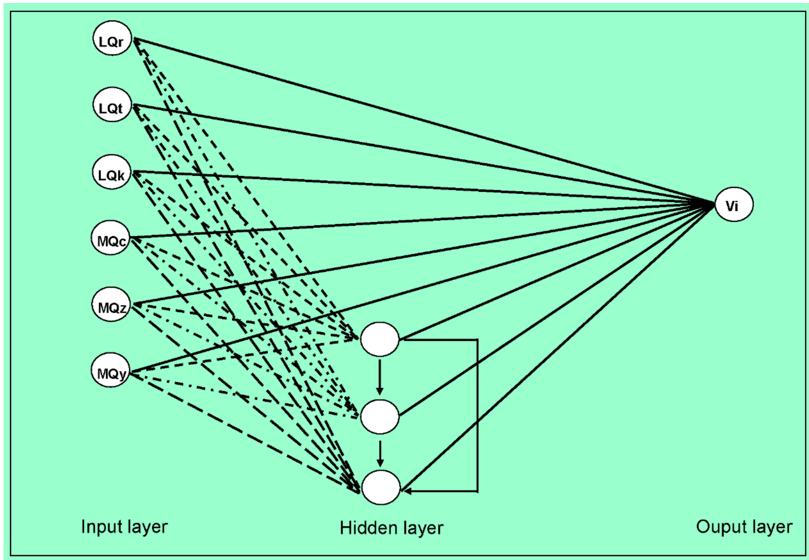
The *Albero* model of *MicroLEIS DSS* uses polynomial equations to predict yields of wheat, maize, and cotton from soil properties. The *Alcor* and *Aljarafe* models are good examples of soil evaluation methods using multiple regression analysis for predicting soil engineering properties (soil compaction, and soil plasticity and workability, respectively; De la Rosa et al., 1992; Horn et al., 2002).

Neural Networks

These artificial-intelligence-based technologies, which have grown rapidly over the last few years, show good capability to deal with non-linear multivariate systems. Moreover, they can process input patterns never presented before, in much the same way as the human brain does. Recently, connections have emerged between neural network techniques and its applications in engineering, agricultural, and environmental sciences.

An artificial neural network is a computational mechanism that is able to acquire, represent, and compute a weighting or mapping from one multivariate space of information to another, given a set of data representing that mapping (Figure 5.). It can identify subtle patterns in input training data which may be missed by conventional statistical analysis. In contrast to regression models, neural networks do not require knowledge of the

Figure 5. An artificial neural network approach for soil erosion evaluation, combining land and management factors (LQ and MQ) to produce soil vulnerability indexes (Vi). Example: ImpelERO model (Source: Adapted from De la Rosa et al. (1999). With permission)



functional relationships between the input and the output variables. Moreover, these techniques are non-linear, and therefore may handle very complex data patterns which make simulation modeling unattainable. As well as the ability to model a multi-output phenomena, another advantage of neural networks is that all kinds of data–continuous, near-continuous, and categorical or binary–can be input without violating model assumptions. Once the training and testing phases of the neural network analysis are found to be successful, the generated algorithm can be easily put to use in practical applications (Baughman & Liu, 1995).

Within the *MicroLEIS DSS* framework, the *ImpelERO* model uses a neural network type–a variation of the back-propagation network approach–to predict soil loss by water erosion and its impact on crop productivity, and to optimize the agricultural management. In this network model, data from the input layer are fed into one or more hidden layers and a set of connection weights are continually adjusted under the supervised training mode (De la Rosa et al., 1999). Also, the *Sierra2* neural network model analyses a multi-output system to predict soil suitability for a wide selection of forest species (Heredia, 2006).

Hybrid Systems

The combination of dynamic simulation models and empirically based land evaluation techniques are currently producing a cross-fertilization of excellent scientific and practical results, improving the accuracy and applicability of the models. For example, the simulation modelling especially referring to soil/plant-grown/contamination systems is relatively well advanced at the local scale (e.g. process measurement sites, experimental stations, small catchments; Jones et al., 2003), but extrapolation to a regional scale is still a major priority. This extrapolation can be made i) by scaling-up techniques, developing a linkage between the input variables included in the models and information contained in soil survey databases through the development of pedo-transfer functions, or ii) by empirically based land evaluation techniques, combining the results of representative applications of the simulation models and soil survey database information, through the development of meta-models (Simota & Mayr, 1996).

The hybrid approach of Bouma et al. (1993) demonstrates that dynamic simulation modeling results can fit well into expert systems for assessing crop production. This mixed model was obtained in a decision tree of branches based on qualitative data combined with branches using quantitative data obtained by dynamic simulation. Simulation of the soil water regime provided quantitative data for several of the land qualities being distinguished. This dynamic simulation/expert system approach should be preferred to simple qualitative estimates, although not all land qualities can necessarily be characterized by simulation modeling.

In the *MicroLEIS DSS* system, the *ImpelERO* hybrid model was developed using expert decision trees and artificial neural networks for assessing soil erosion risk. This approach offers excellent performance in modeling the complex soil erosion problem, and very good quantification and generalization capability for prediction (De la Rosa et al., 1999; 2000).

Optimization Tools

Land evaluation decision support systems for policy-makers and land users must focus on choosing optimal use and management decisions. In this sense, optimization tools based on land evaluation models are very important in formulating decision alternatives: for example, agricultural management practices to minimize threats to the sustainability of farming systems. Agricultural management operations depending on spatially varying land characteristics have the added difficulty of trying to satisfy multiple, and often opposing, aims: the best soil conditions for plant growth may not be the best with regard to erosion or pollution.

The optimization tools are used in conjunction with running various *MicroLEIS DSS* models. On the basis of the quadratic version of the *Albero* model, a mathematical procedure was followed to find a combination of input variables to maximize predicted yields. This procedure involved taking the first mathematical derivate with respect to each independent variable, setting it to zero, and solving the system of simultaneous equations (De la Rosa et al., 1992). On the basis of the expert-system/neural-network structure of the *ImpelERO* model, a computerized procedure was followed to find an appropriate combination of management practices to minimize soil loss for a particular site (specified climate and soil characteristics). This formulation of specific crop management for soil protection of each particular site is one of the most interesting features of the *ImpelERO* model (De la Rosa et al., 2000).

Application User-Interface

The possibilities for exploitation of land evaluation models in decision-making by developing the model application software or generalization phase are enormous. This phase will make possible the practical use of the information and knowledge gained during the prior phase of building evaluation models (Antoine, 1994). Since the beginning of the *MicroLEIS* project, the emphasis has been on developing the model application software. Three versions were developed for each of the *MicroLEIS DSS* models: PC-, Web-, and GIS-based applications (Figure 1).

PC Version

When the land evaluation models are expressed in notations that can be understood by a calculating device, the algorithms become computer programs. In order to put the models to use in practical applications, i.e. to automate the application of land evaluation models, a library of PC-based software was developed. A graphical interface was also designed which allows the models to be easily applied. This user interface is considered a very important component because, to the user, it *is* the system.

Within the *MicroLEIS DSS* framework, the PC-based software has been written using various programming languages, particularly Basic and C++. It has the following main characteristics: i) input data through the keyboard and connection with the attribute databases; ii) 'pop up' screens showing codes, types, and classes of input variables; iii) models running in individual and batch processing modes; iv) output evaluation results in window, printout and file formats; and v) links of output files with GIS databases. These computer programs are largely self-explanatory.

Web Development

The model computer programs can also be implemented on the Internet through a WWW server, so that users can apply the models directly via a Web browser. It is not necessary to download and install the PC software on their own servers: they can apply it on a per-use basis. These open-access WWW applications offer several advantages, such as their use by many people, allowing their usability to be checked in order to improve the systems. Upgrades are immediately made available on the WWW server. The website is the center of activity in developing operative decision support systems.

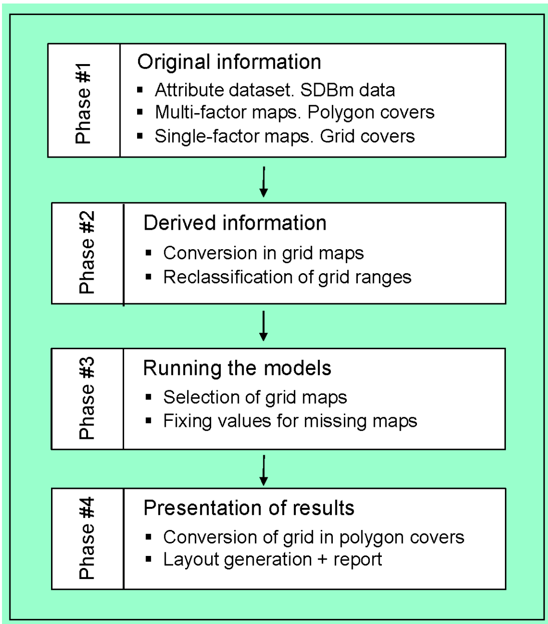
All the *MicroLEIS DSS* models have been translated into PHP for their direct application on the Web. However, this version of the model allows only the individual, point-by-point application of the soil, land, or field-unit being evaluated.

GIS Integration

Spatialization or regionalization analysis includes the use of spatial techniques to expand land evaluation results from point to geographic areas, using soil survey and other related maps. The use of geographical information system (GIS) technology leads to the rapid generation of thematic maps and area estimates, and enables many of the analytical and visualization operations to be carried out in a spatial format, by combining different sets of information in various ways to produce overlays and interpreted maps. Furthermore, digital satellite images can be incorporated directly into many GIS packages. This technology is already a prerequisite for managing the massive datasets required for spatial land evaluation application: a simple map subsystem (e.g. ArcView) being all that is required to show basic data and model results on a map, or to extract information from maps to be used in the land evaluation models. The core objects can be used for retrieving features from the attribute databases (e.g. *SDBm Plus*, *CDBm* or *MDBm*), projecting layers and displaying maps, creation/editing/deletion of spatial objects, querying operations, converting from one coordinate system to another, mapping the projected layers, etc. At this regional scale, the assessments are made from a very broad and generalized perspective. However, this level of assessment is where policy decisions are usually made (Davidson et al., 1994).

The option "Spatialization" of *MicroLEIS DSS* has been developed as a deeper stage of the scaling-up process of evaluation models application (Figure 6). GIS technology was used to extract information from maps to be used in the predictive models, and to show model results on a map. The evaluation results are estimated by grid cell and aggregated to regional level. In the first stage of this general scheme, the soil survey maps, which in geographical format are usually polygon multifactor maps (e.g. Soil Geographical Database of Europe; ESB, 2000), are the main source of basic information. Additional basic information can be extracted from other soil-survey-related maps, such as land use maps (e.g. Corine Land Cover of Europe; EEA, 1995). At regional scale, part of the basic information for applying *MicroLEIS DSS* land evaluation methods can be facilitated

Figure 6. Spatialization process of the models application in MicroLEIS DSS, for expanding land evaluation results from points to geographic areas.



by single-factor grid maps, such as digital terrain models, along with satellite images.

Secondly, to extract information from original maps to be used in each application, a set of derived grid covers are prepared. In this homogenization stage, the spatial resolution or grid cell size is determined by the user depending on the smaller scale of the original covers. The models can then be run directly within the ArcView environment by converting the source codes of the evaluation models to Avenue programming language. This spatial application is made cell-to-cell for the different covers, obtaining a result value for each cell.

As the final stage, the output evaluation results are visualized on a grid cover with the spatial resolution previously fixed. A polygonal evaluation map can also be elaborated by automatic aggregation of the cells with the same result value.

Software Availability

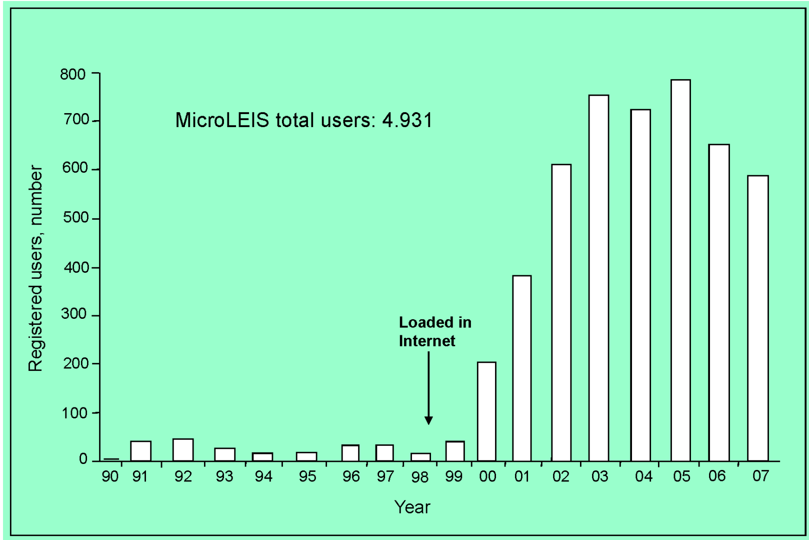
Presently, a spin-off from the CSIC (named *Evenor-Tech*; www.evenor-tech.com) has been launched in basis to the *MicroLEIS* technology. Also, a reduced CD-ROM version of *MicroLEIS DSS* is included into the book "Evaluación Agroecologica de Suelos para un Desarrollo Rural Sostenible" (De la Rosa, 2008).

A CASE STUDY IN CORDOBA PROVINCE (SPAIN)

According to the published results, the different components of *MicroLEIS DSS* have been applied by agro-environmental researchers of diverse disciplines. For example, practical applications of the *SDBm Plus* database include ongoing environmental renewal projects in Eastern Europe supported by the World Bank. It has been used to record the condition of contaminated or depleted soils before and after land restoration projects, and to guide the assessment of project investments and follow-up actions. This software is also being used by the Consultative Group on International Agricultural Research (CGIAR) to facilitate technical research and development planning decisions on an international scale (FAO-UNEP, 1999). Recently, the German Federal Institute for Geosciences and Natural Resources has adopted the terminology and components of the *SDBm Plus* for its FAO soil database version (Eckelman, 1999).

The evaluation models have also been widely applied in studying suitability and vulnerability risk for different agricultural systems and many geographical areas. Researchers from Mediterranean regions have made use of *MicroLEIS DSS* models to produce land evaluation maps for major crops, and erosion and contamination risk (Davidson et al., 1994; Navas & Machin, 1997). Many of these applications have followed up with validation analysis, good agreement being obtained between the predictive results and those

Figure 7. Number of registered MicroLEIS DSS users since 1990.



measured or estimated by other methods. In one application described by Farroni et al. (2002), a modified version of the *Raizal* model was developed and validated in Central Italy to quantify sediment transport by relying on qualitative classes of soil erosion risk.

In many past studies, researchers accepted the evaluation models in *MicroLEIS DSS* as they were; others showed that adaptations and improvements were needed. In some cases, researchers modified the programming code to create their own versions of models in order to apply them in particular geographical conditions (Bojorquez, 1999). In addition to research applications (Figure 7), the *MicroLEIS DSS* system has been used in teaching in formal university courses at graduate and undergraduate levels, such as in the land evaluation courses of the Department of Soil Science and Geology of Wageningen Agricultural University (Van Mensvoort & Booltink, 2001).

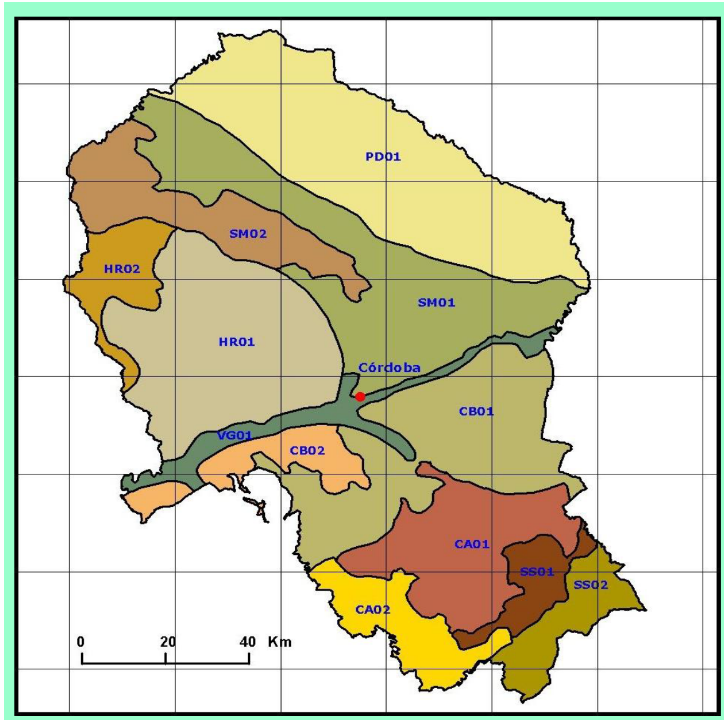
In this case study, the land evaluation models of *MicroLEIS DSS* system were applied in selected benchmark areas of Cordoba Province, Spain, in order to design the most sustainable agricultural land use and management practices.

Benchmark Sites

In the Mediterranean province of Cordoba, Andalucia region, Southern Spain, the climate is semi-arid, with mild rainy winters, and hot dry summers of high solar radiation and a high rate of evaporation. This seasonal contrast is exacerbated by the erratic and unpredictable rainfall distribution from year to year, and crops can suffer from moisture deficits even during years receiving the mean precipitation.

In the Mediterranean region, agricultural red and reddish-brown soils, of heavy-textured topsoil and permeable subsoil, are basically developed over calcareous materials (Alfisols and Inceptisols). They are very sensitive to water erosion. Heavy dark clay soils are developed in level areas and depressions (Vertisols). These soils, of high natural fertility, present management problems because of unfavorable physical properties and shrink/swell characteristics. Both red and dark soils, along with alluvial Entisols, are used extensively for Mediterranean crop production: annual crops, olive, vineyards, and citrus. Non-agricultural shallow and stony soils (Entisols, Inceptisols, and Alfisols) of the uplands,

Figure 8. Location of the selected 12 benchmark sites within the Mediterranean province of Cordoba, Southern Spain.



over calcareous and non-calcareous materials, are dominated by wooded pasturelands ("dehesa" in Spanish language) which are considered very appropriate land use systems for these poor soils (Verheye & De la Rosa, 2005).

On the basis of the semi-detailed natural resources surveys of Cordoba province, 12 benchmark sites were selected (Figure 8). A general description of each site is summarized in Table 3. The approximate geographic coordinates of Cordoba province are 37º 15‘to 38º 41‘N and 3º 54‘to 5º 38‘W. Its slopes range from < 2 to 30%, and the elevation is from 40 to 1,560 m above sea level. The total province area is 1,377,877 ha. For each of the benchmark site, a representative meteorological station was selected, based on monthly mean climate variables for the long period 1961-1990. The typical soils were selected because they occupy large proportions of the corresponding natural region. The morphological and analytical properties of the typical soil profiles were taken from the soil profile database of SEISnet (De la Rosa, 2001).

Land Use Planning

Agricultural land use decisions in the selected 12 benchmark sites of Cordoba province based on *MicroLEIS DSS* models (De la Rosa et al., 2004) are presented in two major groups: land use planning and land use management. As shown in Table 3, land use planning decisions are supported essentially by land capability and land suitability models, and land use management decisions or soil management recommendations by land vulnerability models. Land use planning is generally aimed at a regional level, and land management at a farm level.

It must not be forgotten that each application of *MicroLEIS* models does not necessarily reflect

Table 3. General description of the selected 12 benchmark sites in the Mediterranean province of Cordoba, for applying the MicroLEIS DSS.

Benchmark site	*Natural region*	*Typical soil profile*[a]	*USDA-98 classification*	*Average slope (%)*	*Elevation (m)*
CA01	Campiña Alta	CO0101	Rendollic Xerorthent	5 - 10	240
CA02	Campiña Alta	CO0109	Calcic Rhodoxeralf	5 - 10	300
CB01	Campiña Baja	CO0201	Typic Chromoxerert	2 - 5	130
CB02	Campiña Baja	CO0210	Typic Haploxeralf	2 - 5	150
HR01	Hornachuelos	CO0202	Ruptic Xerochrept	10 - 15	620
HR02	Hornachuelos	CO0302	Lithic Xerorthent	10 - 15	260
PD01	Pedroches	CO0501	Typic Xerochrept	2 - 5	670
SM01	Sierra Morena	CO0305	Lithic Xerorthent	5 - 10	300
SM02	Sierra Morena	CO0309	Ruptic Palexeralf	5 - 10	200
SS01	Sierra Sur	CO0601	Lithic Rhodoxeralf	15 - 30	1020
SS02	Sierra Sur	CO0701	Gypsic Xerochrept	15 - 30	250
VG01	Vega	CO0203	Typic Xerofluvent	< 2	80

[a]From the SEISnet soil profile database (De la Rosa, 2001).

the land properties of the whole natural region of Cordoba province. Although typical soils were selected because they occupy large proportions of the natural regions, inclusions of soils significantly different in each region can be recognized. Therefore, the results of this benchmark site analysis of soil use and management must not be extrapolated to large geographical areas without additional spatialization studies.

Soil or land use planning, relating major land use to soil capability and soil suitability for each particular site, is considered the first objective in achieving environmental sustainability. Any kind of agricultural management system will have a negative environmental impact when applied on land with very low suitability for agricultural uses. In the Mediterranean region, for example, marginal agricultural land under any kind of farming system is the ideal scenario for soil erosion.

Table 4. Bioclimatic deficiency and land capability evaluation results from application of the Terraza and Cervatana qualitative models, respectively.

Benchmark site	*Bioclimatic deficiency[a] (GPL, day)*	*Land capability class[b]*	
		Best agricultural land	**Marginal agricultural land**
CA01	210	S2lrb	
CA02	210	S2lrb	
CB01	240	S2l	
CB02	240	S2l	
HR01	180		S3tlb
HR02	180		Nl
PD01	180		S3lb
SM01	180		S3lrb
SM02	180		S3tlb
SS01	210		Ntr
SS02	210		S3tr
VG01	240	S1	

[a]GPL, length of growing period.

[b]**Land capability classes:** S1: Excellent; S2: Good; S3: Moderate; N: Not suitable.

Limitation factors: t=topography: slope type and slope gradient; l=soil: useful depth, texture, stoniness/rockiness, drainage, and salinity; r=erosion risk: soil erodibility, slope, vegetation cover, and rainfall erosivity; b=bioclimatic deficiency (GPL)

Arable Land Surfaces

Results of applying *Terraza* (bioclimatic deficiency) model and *Cervatana* (land capability) model in the selected 12 benchmark sites are shown in Table 4. Five application sites are classified as arable or best agricultural lands, and another 7 as marginal or unsuitable lands. The Vega site (VG01: Typic Xerofluvent soil) and the Campiña Baja sites (CB01: Typic Chromoxerert soil, and CB02: Typic Haploxeralf soil) present the highest capability for most agricultural crops; in contrast, the Hornachuelos site (HR02: Lithic Xerorthent soil) and the Sierra Sur site (SS01: Lithic Rhodoxeralf soil) show the most-unfavorable conditions. The length of the growing period, the slope, and the soil depth are the major limitation factors in this agro-ecological zoning classification of Cordoba sites.

Despite these land capability results, many similar areas classified as marginal or unsuitable lands are currently dedicated to agricultural use. Some current land uses are entirely wrong with respect to agro-ecological potentialities and limitations. Changes in land use from natural habitat to intensively tilled agricultural cultivation are one of the primary reasons for soil degradation. Deforestation for agricultural needs and overgrazing has led to severe erosion in the past. Usually, increasing agricultural land capability correlates with a decrease in the soil erosion process. In summary, a positive correlation between current land use and potential land capability would be necessary (De la Rosa & Van Diepen, 2002).

Semi-Natural Habitats

Results of applying *Sierra* (forestry land suitability) model in the 7 benchmark sites previously classified as marginal or unsuitable lands are shown in Table 5. This model identifies those Mediterranean forest communities that can be created on ex-agricultural land, according to the tolerance ranges for standard soil and climate variables of 61 forest species (22 trees and 39 shrubs). For the tree species, stone pine (*Pinus pinea*), swamp pine (*Pinus maritima*), and red eucalyptus (*Eucalyptus camaldulensis*) are the most-viable forest species for restoration of semi-natural habitats in marginal areas of Cordoba. The maximum number of forest species was found for the Pedroches site (PD01: Typic Xerochrept soil), while the Hornachuelos site (HR02: Lithic Xerorthent soil) returned no viable species. For the shrub species, gorse (*Ulex parviflorus*) and mastic tree (*Pistacia lentiscus*) are the most-viable species for reforestation. It is interesting to note the different number of viable tree species in comparison with the number of viable shrub species predicted for the Hornachuelos site (HR02: Lithic Xerorthent soil), which appears to be due to the different influence of the soil factor useful depth in both cases.

According to these results, it is clear that in many of the marginal agricultural lands, it can be necessary to change the land use system fundamentally: for example, by conversion from arable to forest or pasture. For this, the viability of converting set-aside lands into semi-natural habitats must be evaluated. Gilbert et al. (2000) suggest a similar methodology to identify those forest communities that can be created on ex-agricultural land, using soil and climate variables in comparison with the tolerance ranges of selected forest species. In order to adopt also agro-forestry strategies, the land evaluation results of *Sierra* model can be combined with those predicted by the *Almagra* model for selecting the best combination of trees and crops to produce maximum environmental benefits in each particular site.

Crop Diversification

Results of applying the *Almagra* (agricultural soil suitability) model in the 5 benchmark sites previously classified as agricultural lands are shown in Table 6. For this qualitative model, matching tables following the principle of maximum limitation for soil factors are used to express soil suitability classes for 12 Mediterranean crops. Sunflower (*Helianthus annus)* and winter wheat (*Triticum aestivum*) are the most-suitable crops for most of the sites, and citrus (*Citrus sp.*) and peach (*Prunus persica*) the least suitable. The Vega site (VG01: Typic Xerofluvent soil) has nearly ideal physical and chemical soil properties for most crops. The Campiña Baja site (CB01: Typic Chromoxerert soil) also presents very good conditions for annual crops, but not for perennial ones. This is due to a high clay content and a low infiltration of water in these soils.

The productivity index calculated by application of the *Albero* statistical regression model

Table 5. Forestry land suitability evaluation results from application of the Sierra qualitative/neural network model to the marginal lands.

Benchmark site	*Viable forest species*
Tree species	
HR01	Black pine (*Pinus pinaster*), stone pine (*Pinus pinea*), white eucalyptus (*Eucalyptus globulus*)
HR02	No viable species
PD01	Black pine, cork oak (*Quercus suber*), holm oak (*Quercus ilex*), muricated oak (*Quercus muricata)*, red eucalyptus (*Eucalyptus camaldulensis*), stone pine, swamp pine (*Pinus maritima*), turkey oak (*Quercus cerris*), white eucalyptus
SM01	Stone pine, swamp pine, holm oak, red eucalyptus
SM02	Red eucalyptus
SS01	Holm oak, swamp pine
SS02	Holm oak, stone pine, swamp pine
Shrub species	
HR01	Gorse (*Ulex parviflorus*), phillyrea (*Phillyrea angustifolia*), prickly juniper (*Juniperus oxycedrus*), strawberry tree (*Arbutus unedo*), wrinkled leaf rockrose (*Cistus crispus*)
HR02	Broom-like-kidney-vetch (*Anthyllis cytisoides*), dwarf fan palm (*Chamaerops humilis*), italian buck-thorn (*Rhamnus alaternus*), kermes oak (*Quercus coccifera*), lygos (*Retama sphaerocarpa*), mastic tree (*Pistacia lentiscus*), rock rose (*Cistus albidus*), rosemary (*Rosmarinus officinalis*),
PD01	Gorse, sage-leaved (*Cistus salviifolius*)
SM01	Hawthron (*Crataegus monogyna*), myrtle (*Myrtus communis*), phillyrea, prickly juniper
SM02	Broom-like-kidney-vetch, dentate lavender (*Lavandula dentata*), dwarf fan palm, gorse, kermes oak, lygos, mastic tree, rockrose, rosemary, small buckthorn (*Rhamnus lycioides*)
SS01	Gorse, hawthorn, mastic tree, phillyrea, prickly juniper, rosemary-leaved rockrose (*Cistus clusii*), sloe (*Prunus spinosa*), strawberry tree
SS02	Broom-like-kidney-vecth, dentate lavender, dwarf fan palm, kermes oak, lygos, mastic tree, rockrose, rosemary, small buckthorn

Table 6. Soil suitability evaluation results from application of the Almagra qualitative model to the agricultural lands.

Benchmark site	*Soil suitability class*[a]											
	Wheat (*Triticum aestivum*)	**Corn (*Zea mays*)**	**Melon (*Cucumis melo*)**	**Potato (*Solanum tuberosum*)**	**Soybean (*Glycine max*)**	**Cotton (*Gossypium hirsutum*)**	**Sunflower (*Helianthus annus*)**	**Sugar beet (*Beta vulgaris*)**	**Alfalfa (*Medicago sativa*)**	**Peach (*Prunus persica*)**	**Citrus (*Citrus sp.*)**	**Olive (*Olea europaea*)**
CA01	S3c	S3c	S3c	S4c	S3c	S3c	S3c	S3c	S3c	S4c	S4c	S3tc
CA02	S3t	S3t	S3t	S3t	S3t	S3t	S3t	S3t	S3t	S3p	S3p	S3p
CB01	S2t	S2tc	S2tc	S2tc	S2t	S2tca	S2t	S2ta	S2t	S4t	S4t	S4t
CB02	S3d	S2dc	S2dc	S2dc	S3d	S2ptd	S2ptd	S3d	S3d	S4td	S4td	S4dc
VG01	S1	S2c	S2c	S2c	S1	S2ca	S1	S2a	S1	S2c	S2c	S1

[a]**Soil suitability classes:** S1: Optimum; S2: High; S3: Moderate; S4: Marginal; S5: Not suitable.

Soil limitation factors: p: useful depth; t: texture; d: drainage; c: carbonate content; s: salinity; a: sodium saturation; g: profile development.

(Table 7) demonstrates the optimum soil physical/chemical quality of the Vega site (VG01) and of the Campiña Baja site (CB01).

In relation to these soil evaluation results, it is interesting to note that simplification of crop rotation as a relevant element of arable intensification has led to soil deterioration and other negative ecological impacts (Stoate et al., 2001). Within agricultural lands, all soils can be used for almost any crop if sufficient inputs are supplied. The inputs can be such that they dominate the conditions under which crops are grown, as may be the case in greenhouse cultivation. However, each soil unit has its own agro-ecological potentialities and limitations, and each crop its biophysical requirements. In order to minimize the socio-economic and environmental costs of such inputs, the second major objective of land use planning is to predict the inherent suitability of a soil unit for supporting a specific crop over a long period of time. This kind of study provides a rational basis to diversify an agricultural soil system, considering all the possible crops (De la Rosa & Van Diepen, 2002). Soil productivity for major crops can also be used to select the most appropriate crop for each particular site.

Vulnerability Area Identification

Results of applying *Raizal* (soil erosion risk) model in the 5 agricultural benchmark sites, showing vulnerability class and soil erosion loss for each site are shown in Table 8. The biggest risks are obtained for the traditional olive crop, with the Campiña Baja site (CB01: Typic Chromoxerert soil) presenting the highest sensitivity, with a soil loss very close to 10 t/ha/year.

This identification of areas vulnerable to soil degradation are helpful for improving knowledge about the extent of the areas affected and, ultimately, for developing measures to control the problem. For example, because of the very slow rate of soil formation, any soil loss of more than 1 t/ha/year can be considered irreversible within a time span of 50-100 years. Losses of 20 to 40 t/ha in individual storms, which may occur once

Table 7. Agricultural soil productivity evaluation results from application of the Albero statistical model to the agricultural lands.

Benchmark site	*Predicted yield (t/ha)*		
	Rainfed wheat	**Irrigated corn**	**Irrigated cotton**
CA01	3.93	6.33	2.86
CA02	3.02	6.07	3.49
CB01	4.39	8.06	3.42
CB02	3.18	5.23	2.73
VG01	4.14	6.95	3.19

Table 8. Soil erosion evaluation results from application of the Raizal expert system model: Vulnerability class[a] and soil erosion loss, in t/ha/year, to the agricultural lands.

Benchmark site	*Attainable risk[b]*	*Actual risk*			
		Extensive wheat	**Intensive sugar beet**	**Extensive sunflower**	**Traditional olive**
CA01	V7 t (7.16)	V7 (7.16)	V8 (7.93)	V9 (8.69)	V10 (9.42)
CA02	V5 k (5.52)	V6 (6.36)	V7 (7.16)	V8 (7.93)	V9 (8.69)
CB01	V8 kr (7.93)	V8 (7.93)	V9 (8.69)	V9 (8.69)	V10 (9.42)
CB02	V1 (1.60)	V2 (2.73)	V2 (2.73)	V3 (3.73)	V3 (3.73)
VG01	V5 r (5.52)	V6 (6.36)	V7 (7.16)	V8 (7.93)	V9 (8.69)

[a]**Vulnerability classes:** V1: None; V2: Very low; V3: Low; V4: Moderately low; V5: Slightly low; V6: Slightly high; V7: Moderately high; V8: High; V9: Very high; V10: Extreme.

Degradation factors: t: relief; k: soil erodibility; r: rainfall erosivity.

[b]For attainable risk, the anthropogenic factors are not considered.

Table 9. Soil fertility capability evaluation results from application of the Marisma qualitative model to the agricultural lands.

Benchmark site	**FCC class[a]**	**Diagnostic report**
CA01	LLgdb	Surface crusting, good subsoil texture, drainage needed, flush of N, Fe and Zn deficiency
CA02	LLdb	Surface crusting, good subsoil texture, flush of N, Fe and Zn deficiency
CB01	CCgdbv	Surface soil loss, drainage needed, flush of N, Fe and Zn deficiency, no work when wet, difficult tillage
CB02	LCd	Surface soil loss, flush of N, no work when wet
VG01	LLdb	Surface crusting, good subsoil texture, flush of N, Fe and Zn deficiency

[a]**Soil and subsoil types:** L: loamy; C: clay.

Soil modifiers: g: gley conditions; d: annual dry period; b: free carbonate material; v: heavy soil with expansive clay.

every two or three years, are measured regularly in Mediterranean areas, and in extreme events, there can be a loss of more than 100 t/ha (Morgan, 1992).

Table 9 shows the results of applying the *Marisma* (soil fertility capability) model in the 5 agricultural benchmark sites. This model gives special emphasis to the soil chemical quality, but also considers several soil physical parameters related with the textural class. The presence of free carbonates in the soil of all the sites except Campiña Baja (CB02: Typic Haploxeralf soil) can be an agricultural disadvantage in relation to minor elements availability such as Fe and Zn. Several soils (CA01, CA02 and VG01 sites) exhibit the phenomenon of surface crusting, which causes problems for crop emergence and for soil tillage, such as it is very frequently in many Mediterranean soils.

Soil Management Planning

In order to define site-specific strategies of sustainable agriculture, soil management analysis must be a second phase after land use planning. It is obvious that the increasing use of mechanized cultivation has led to a substantial increase in rates of soil degradation. However, agricultural intensification is not necessarily or directly related to soil degradation. For example, soil degradation in an intensive farming system using soil protection practices may be lower than in a more extensive system that does not apply them. In Mediterranean areas, it is clear that water erosion is the major soil degradation process. To reduce the soil erosion risk and related soil degradation processes, the soil management practices (particularly the tillage system) must be formulated for each particular site (De la Rosa et al., 2000; Simota et al., 2005). Water erosion has negative impacts: not only at the site where soil is lost but also in the water systems where the material accumulates. Local impacts include loss of organic matter and nutrients, and diminished infiltration and water availability. Remote impacts include lower quality water supplies, siltation (which impairs drainage and maintenance of navigable river channels and irrigation systems), and increased frequency and severity of floods. Runoff is the most important direct driver of severe soil erosion, and therefore processes that influence runoff play a significant role in any analysis of soil erosion intensity. Management practices that reduce runoff are critical in effective soil protection (Grimm et al., 2001).

Organic Matter Restoration

The recommended crop residues treatment for various testing crops in the 5 agricultural benchmark sites, by application of the *ImpelERO* (erosion/impact/mitigation) model are shown in Table 10. The most-repeated option for each crop and land area is to bury in the soil the maximized crop residue; being collected or burned options considered only in rare cases. These soil evaluation results try to avoid the negative consequences of tillage practices that strongly accelerate soil erosion processes by destroying soil organic matter and soil structure. Loveland et al. (2000) recorded a decrease in mean soil organic carbon from arable ley sites of 0.49% over a 15-year period. Increasing the soil organic matter levels is critical for sustainable agriculture. The best way to increase the stable soil organic matter is to improve crop yields that maximize crop residues for incorporation into the soil. In general terms, it has been estimated that an annual return of 5 t/ha of crop residues could keep soils in equilibrium with present levels of soil organic matter. The efficiency of conversion of that carbon to stable soil organic matter is not constant, and depends on several variables (Wallace, 1994).

Tillage Intensity

The recommended management practices from application of the *ImpelERO* (erosion/impact/mitigation) model for various testing crops in the 5 agricultural benchmark sites are shown in Table

Table 10. Recommended agricultural management practices according to the predicted soil erosion from application of the ImpelERO neural network model.

Benchmark SiteRainfed wheat	Management characteristic					
	Row spacing (m)	**Residues treatment**	**Tillage direction**	**Operation sequence (number)**	**Operation Roughness[a] (mm)**	
CA01	0.15	Buried	Contour	2	20-25	
CA02	0.15	Buried	Contour	4	<20	
CB01	0.15	Buried	Contour	1	-	
CB02	0.15	Buried	Contour	2	20-25	
VG01	0.15	Collected	No matter	4	<20	
Irrigated sugar beet						
CA01	0.60	Buried	Contour	6	<20	
CA02	0.60	Buried	Contour	6	<20	
CB01	0.60	Buried	Contour	6	20-25	
CB02	0.60	Buried	Contour	6	<20	
VG01	0.60	Collected	No matter	6	20-25	
Rainfed sunflower						
CA01	0.75	Buried	Contour	3	20-25	
CA02	0.75	Buried	Contour	5	<20	
CB01	0.75	Buried	Contour	3	>25	
CB02	0.75	Buried	Contour	5	<20	
VG01	0.75	Collected	No matter	5	<20	
Traditional olive						
CA01	10	Buried	Contour	3	>25	
CA02	10	Buried	Contour	5	20-25	
CB01	10	Buried	Contour	3	>25	
CB02	10	Buried	Contour	5	20-25	
VG01	10	Collected	No matter	5	20-25	

[a]The overall value, expressed in millimeters, determined by the operation number and the random roughness of each operation implement used.

10. The soil tillage practices are formulated for each specific site in relation to the tillage direction, operation sequence, and roughness produced, as a set of concrete measures against water erosion. The implement types used for each operation sequence are also recommended by *ImpelERO* model. In the Vega site (VG01: Typic Xerofluvent soil), tillage direction is irrelevant because of the low slope of this area. Independent of tillage intensity, tillage direction is considered because sediment transport is much more rapid with plowing up and down the slope than it is along the contour. Moreover, contour tillage can move material either up and down, depending on the direction in which the tillage turns the soil: contour tillage in which the soil is turned uphill moves rather less material.

According to the physical and chemical properties of the dominant soil (Typic Chromoxerert) in the Campiña Baja site (CB01), the number of tillage operations can be greatly reduced for a wheat crop (Table 10). This soil tillage intensity can range from full-width maximum tillage to zero tillage (i.e. intensive tillage, reduced tillage, plowless tillage, minimum tillage, and no-tillage). The most common highly intensive tillage system of dry farming consists of: moldboard plowing to break the hardened soil surface, and much surface disking and harrowing to reduce soil clod size and to control weeds. This repeated tillage system accelerates decomposition of organic matter, thus affecting soil physical, chemical, and biological attributes of soil quality. It is clearly inappropriate for most soils, and must be avoided if soil erosion is to be combated.

On the contrary, in the no-tillage system the soil is left undisturbed, and includes: direct sowing, and weed control with herbicides. Several studies show a continuous increase in organic matter and improvement in soil structure, restoring and improving soil quality, and that crop yields increase, and soil erosion is controlled (e.g. Tebrugge & During, 1999). No-tillage has gained wide acceptance in Australia and North and South America, but its adoption has been very slow elsewhere. Some studies (e.g. Arshad, 1999) indicate that the level of success in the no-tillage system varies with: crop species, soil type, climatic conditions, and length of growing season.

With regard to the micro-topography or random roughness (Table 10) of the soil surface produced by tillage, conventional implements (e.g. plow moldboard) that cause soil inversion are particularly appropriate for slope soils, due to the high surface roughness (> 30 mm). Increasing the surface roughness decreases the transport capacity and runoff detachment by reducing the flow velocity. During a rainfall event, rough surfaces are eroded at lower rates than are smooth surfaces under similar conditions.

Workability Timing

The optimum water content for tillage, by application of the *Aljarafe* (soil plasticity and workability) model, in the 5 agricultural benchmark sites is shown in Table 11. This model estimates the optimum workability in terms of particle size distribution, cation exchange capacity, and organic matter content. The vertic soil of the Campiña Baja site (CB01: Typic Chromoxerert soil) presents many difficulties for tillage because the optimum water content is only 13%. The soil workability status ("tempero" in Spanish) is considered as the optimum soil water content where the tillage operation has the desired effect in producing the greatest proportion of small aggregates (Dexter and Bird, 2001). The soil workability status for each soil and tillage operation is closely related with the surface roughness produced. Outside this range, the soil is too wet or too dry, and therefore the tillage operation adversely alters the soil physical properties and facilitates soil erosion. Topsoil

Table 11. Recommended agricultural management practices according to the predicted soil workability and subsoil compaction from application of the Aljarafe and Alcor statistical models, respectively.

Benchmark site	Management characteristic[a]		
	Optimum workability (%)	**Wheel load (kN)**	**Tire inflation pressure (kPa)**
CA01	26	17 – 30	60 – 160
CA02	23	< 17	< 60
CB01	13	< 17	< 60
CB02	19	> 30	> 160
VG01	14	17 – 30	60 – 160

[a]Wheel load and tire inflation pressure are related to subsoil compaction risk.

pulverization by repeated tillage and under dry soil conditions has a very negative effect on erosion. Finely pulverized soils are usually smooth, seal rapidly, and have low infiltration rates, as might be the case for some rototilling operations or for repeated cultivation of silt loam soils under dry conditions. Therefore, the water workability limits for each soil and operation, or the number of work days available for tillage, can be considered in order to reduce the soil erosion effects. Soil workability time is the number of days when the soil can be worked after rain. Soil workability is good when the soil can be tilled easily, including reductions in implement draft forces and increases in soil friability.

Machinery Type

The recommended wheel load and tire inflation pressure of machinery, by application of the *Alcor* (subsoil compaction and trafficability) model, in the 5 agricultural benchmark sites are shown in Table 11. The soils of the Campiña Alta (CA02: Calcic Rhodoxeralf soil) and Campiña Baja (CB01: Typic Chromoxerert soil) sites are the most sensitive to subsoil compaction, and must therefore be managed with machinery of less weight and lower tire inflation pressure. Subsoil compaction is considered to be caused by tillage and traffic of increasingly heavy agricultural machinery. The increased density of the soil just beneath the depth of tillage is one of the most striking effects of management systems, especially plowless tillage. Increased soil bulk density reduces the permeability to air, the hydraulic conductivity, and—sometimes—the root development. Soil compaction has been identified as one of the leading problems causing soil degradation, reducing soil productivity, and increasing soil erosion and runoff. Field experiments reported by Canillas & Salokhe (2002) showed that corn yield was reduced by up to 1.11 t/ha when the bulk density was increased from 1.53 to 1.62 g/cm3 in heavy clay soil. This problem is especially severe in soils that are heavy-textured and poorly drained. The compaction risk or vulnerability of agricultural soils, measured by the pre-compression stress, can be used to give recommendations for site-specific farming systems (e.g. implement type, wheel load, and tire inflation pressure). It can also enable the agricultural machine industry to develop site-adjusted machines to support the ideas of good farming practices (Horn et al., 2002). Also, the wheelways must be permanent and be used for all wheel traffic for all field operations.

Soil Input Rationalization

The probability of agro-chemical diffuse contamination, by application of the *Arenal* and *Pantanal* (general and specific soil contamination risk) models, for the respective target crops (annual crops and fruit plantations) in the 5 agricultural benchmark sites is shown in Table 12. In order to rationalize the agro-chemical application, the lowest vulnerability (V1) for most of the contaminant types (N and P fertilizers, heavy metals, and pesticides) is predicted for soils that have low runoff and infiltration rate and are rich in clay and carbonate content, such as CA02 (Calcic Rhodoxeralf soil) and CB01 (Typic Chromoxerert soil) sites. Independently of the nutrient needs for crop yield, the application of fertilizers is considered that usually exceeds the functional capacity of the soil to retain and transform such nutrients. In many cases, the saturation of the soil with nitrogen and phosphate has led to losses of nitrates into shallow groundwater and saturation of the soil with phosphate, which may also move into the groundwater (Zalidis et al, 2002).

The application risk of urban wastes (basically sewage sludge and compost; Table 12) on agricultural soil has been predicted by the analysis of three components relevant to soil protection: organic matter content, nutrient load, and contaminant load. It is very important to select appropriate sites for the application of these further supplies of organic matter and nutrients, evaluating the

Table 12. General and specific soil contamination evaluation results from application of the Arenal and Pantanal expert system models, respectively: Vulnerability class[a].

	General risk	Maximum specific risk			
		N-fertilizers	**P-fertilizers**	**Urban wastes**	**Pesticides**
Annual crops					
CA01	V2	V3	V2	V3	V3
CA02	V1	V2	V1	V1	V2
CB01	V1	V2	V1	V1	V1
CB02	V2	V3	V2	V3	V4
VG01	V1	V2	V1	V1	V3
Fruit plantations					
CA01	V2	V4	V2	V3	V4
CA02	V1	V2	V1	V1	V3
CB01	V1	V2	V1	V1	V2
CB02	V2	V4	V2	V3	V4
VG01	V1	V3	V1	V1	V3

[a] Vulnerability class of predicted ground-and-surface-water contamination: V1: None; V2: Low; V3: Moderate; V4: High; V5: Extreme.

soil contamination vulnerability (particularly regarding heavy metals).

The maximum specific risk from the extensive use of pesticides (Table 12) is due to the leaching and drainage of pesticides into the surface and groundwater. Several soil functions can be degraded, including the food web support, the retention and transformation of toxicants and nutrients, and soil resilience. Today, the frequent use of herbicides is drastically changing the methods of crop production, but their impacts on soil quality/degradation are still not known exactly. Chemical weed control is identified as an important limiting factor in the adoption of the no-tillage system. In this case, the risk of soil contamination by herbicides must be analyzed because, ironically, farming practices to remedy eroded soils can increase soil degradation by contamination.

Testing Analysis

As a part of this project, regional and local real information was compiled for the selected 12 benchmark sites of Cordoba province to testing degrees of success. Testing analysis involves comparison of outputs of *MicroLEIS DSS* models with real information and a determination of the DSS suitability for an intended purpose. Real information represents field data on the aspects for which the models are being tested. During the modeling development phase, each model was already validated including generally calculation of standard errors, root mean square error, slope and intercept of regression, and correlation of observed vs. predicted results (e.g. *ImpelERO* model; De la Rosa et al., 1999). Also, other scientists have tested the models over diverse regions exposing models to new and different environments and testing model robustness (e.g. Farroni et al., 2002). This latter approach was followed in the Andalucian study of climate change impacts on soil degradation by using the *Raizal* and *Pantanal* models in different climate scenarios (De la Rosa et al., 1996).

In relation to the applications of *MicroLEIS DSS* for land use planning decision support at a regional level, Table 13 shows a comparison of predicted vs. present land uses. The predicted land capability values were simulated by extrapolation from benchmark site results applying the *Cervatana* model to the corresponding natural region. The relationship between predicted land capability and present land use from statistical records is clearly unbalanced. About 160,000 ha of rainfed agricultural lands must be changed to forestry,

Table 13. Comparison between extrapolated agro-ecological capability areas and present land use in Cordoba province.

Category	Extension (ha)	Percentage (%)
Predicted land capability class[a]		
Excellent agricultural lands (S1)	49,584	4
Good agricultural lands (S2)	411,249	30
Marginal agricultural lands (S3)	834,421	60
Not suitable (N)	82,623	6
Present land use type[b]		
Irrigation agricultural lands	56,163	4
Rainfed agricultural lands	612,034	44
Forestry, grazing, natural lands	675,385	49
Others	34,295	3

[a]Results by extrapolating application of the *Cervatana* model from the benchmark sites to the corresponding natural regions.
[b]Values from the Corine Land Cover 2000 Project (IGN, 2004)

grazing or natural lands in order to get a better equilibrium in comparison with the moderately or clearly marginal lands. Similar situations are very frequent in the Mediterranean region, and it is, for example, the major reason for the reforestation program launched by the European Commission. According to our own experience with the *Albero* model application results, comparison analysis of calculated vs. observed crop yield showed that the model reproduced observed or real yields in Cordoba province when accurate soil, crop and management information was available.

For the applications of *MicroLEIS DSS* to soil management decision support at a farm level, supported strategies have been specially related to the organic matter restoration, formulation of soil tillage techniques, timing and type of machinery, and rationalization of soil input application. Farm-specific field information on these aspects is difficult to obtain due to the many interactions between environment and management factors. Management options related to agricultural production are not considered in *MicroLEIS DSS*, such as fertilizer, irrigation and pest management, difficulting the measure of environmental responses. From experimental studies in the Mediterranean region, and particularly relative to soil tillage intensity, many results demonstrate the ability of the *MicroLEIS DSS* in formulating site-specific management strategies. For example, a short growing period (GPL < 250 days; such as in Scandinavia or the Mediterranean region) was considered by Arshad (1999) as a barrier to adoption of the no-tillage system. Also, high slope gradient (> 15%) appears to be a limiting factor for the introduction of no-tillage farming systems (Martinez-Raya, 2003). Gomez et al. (1999) demonstrated that the effects of no-tillage in soils with low infiltration rate and that are prone to surface crusting increase runoff generation and soil erosion. They observed the best results of no-tillage system on the heaviest clay soils (Vertisols). Murillo et al. (2004) reported that the long-term effect of reduced tillage systems produced the best results in annual crop rotation, with improved soil quality and crop development. However, such as reported by Lal (2005), the impact of tillage intensity on soil quality is a debatable issue. Some soil scientists and agronomists believe that tillage can adversely affect soil quality and, in contrast, others argue that tillage improves soil quality.

In general terms and for each particular site, it appears clear that the environmental impact of agricultural management systems is reasonably predicted in the *MicroLEIS DSS,* with the positive effects on the agro-ecological soil quality as follows: i) increased organic matter, ii) decreased erosion, iii) better water infiltration, iv) more water-holding capacity, v) less subsoil compaction, and vi) less leaching of agro-chemicals to the groundwater. However, in reality as recognized by Oxley et al. (2004), policy formulation and decision making in the environmental field are complex processes involving many individuals and many different forms of knowledge. Nobody believes that support tools can be a decision-making panacea. Rather, they may provide different types of support (eye-openers, argument support, consensus building, and management option evaluation) at different times and are very likely to be temporarily employed within an organization.

FUTURE RESEARCH DIRECTIONS

In the decades ahead, the development of sustainable agricultural systems will require great improvements, not just through biotechnology and chemical use but also via agro-ecological innovations in order to increase the soil quality and the environmental protection. As referred by some agro-ecologists authors (example: Uphoff et al., 2006), in the future “a second paradigm or doubly green revolution” will be necessary that reverses environmental deterioration at the same time that it augments the supply of food. Maintenance and improvement of soil quality is one of the most important prerequisite to get the environmental sustainability.

The modern principle of soil quality, focusing on the biological aspects of soil system, is an extremely valuable one in predicting sustainable soil use and management. However, in the complex task of soil quality assessment, the physic-chemical land evaluation has much to offer. The new focus on biological approaches must not diminish appreciation of the physical and chemical factors, in order to develop an ecological integration of the three sets of factors for sustainable soil systems.

Information and communication technologies (ICTs) are already providing unprecedented power and flexibility plus the possibilities to combine soil quality information and knowledge in novel and productive ways. New advances of these technologies will improve their possibilities for the development and application of DSSs in agro-ecological soil quality assessment: warehousing, modeling, optimization and spatialization tasks.

The sustainability, as the main objective of DSSs in agriculture, is inherently a multi-disciplinary concept; concerning not only ecological and technological aspects but also economic, social, political and other perspectives. Consequently, future efforts in the area of sustainable soil systems will involve integration methodologies considering all these different disciplines.

Within this framework, *MicroLEIS DSS* system, which created a new philosophy in integrated land evaluation for soil use and protection, from science to practice, will focus on two main research directions:

1. To give answers to decision makers to resolve matters concerning global change impacts, mainly referred to climate change. For example, the development of modelling algorithms that can predict the carbon footprint of soil, crop and forest systems to identify the drivers of emissions and reduction and to evaluate the carbon sequestration capacity of theses agro-ecological systems. It will contribute to the development of the Code of Good Practice on Emissions and Reduction Claims.
2. According to the innovations in ICTs, the *MicroLEIS* systems will be redesign in its operating system to standardize and connect all variables between data base warehousing and evaluation modelling modules. Also, the informatics language will be actualized, along with the integration process with Geographic Information Systems. This task will contribute to facilitate the agro-ecological land evaluation process to decision makers of the private sector and public administration that are not presently involved with this kind of methodologies.

CONCLUSION

The knowledge-based decision support system approach used in *MicroLEIS DSS* appears to be a very useful method for responding to the need to bring agriculture and land resources sciences together for decision-makers. Although many of the models have been calibrated with Mediterranean region information, other major components allow universal application.

With a modular framework such as that used in the *MicroLEIS DSS*, the components can be easily used as required for a particular application. For each application, the selection of the most appropriate model, along with the collection of all key information on the sources, may constitute most of the effort. Due to the wide range of data types required for most of the models, the use of the databases–particularly *SDBm Plus* for soil data–is normally the initial step of any application project.

From the case study, the high variability of the results from this agro-ecological land evaluation research in Mediterranean areas demonstrates the importance of using soil information in decision-making regarding the formulation of site-specific soil use and management strategies. There are not universal rules for environmentally sustainable agriculture.

Agricultural land use systems at a regional level, including agro-forestry practices, are well formulated from the land capability, land suitability, and land vulnerability models of the *MicroLEIS DSS*. The agro-ecological zoning analysis enables identification of the most-suitable sites for agricultural uses (Typic Xerofluvent and Typic Chromoxerert soils) and the marginal lands for restoration of semi-natural habitats (basically Lithic soils). Agricultural benchmark sites with Typic Xerofluvent soils allow the maximum diversification of crop rotation and optimum crop production. Within these agricultural lands, vulnerability areas for soil erosion are specially related to Typic Chromoxerert soils.

The proposed agricultural soil management systems at a farm level follow the general trend for environmentally sustainable agriculture: i) increase the level of soil organic matter by maximizing crop residues; ii) follow the contour for tillage direction; iii) reduce tillage intensity; iv) diversify tillage implements; v) consider optimum soil workability; vi) avoid subsoil compaction; and vii) reduce chemical weed control. However, detailed and specific soil management systems are proposed for each particular site, showing the management characteristics: tillage intensity, workability timing and machinery type, the maximum variability. Benchmark sites with Typic Chromoxeret soils are the most sensitive lands for the different management practices analyzed.

According to the testing analysis, the *MicroLEIS DSS* appears to be a good example of advisory/ decision-support tools in the direction of exploiting and disseminating the scientific data and knowledge on environmentally sustainable agriculture. Similar decision tools can be especially useful in compiling new agro-ecological approaches for the prevention of soil degradation based on the within-region variability of soils, climate, land use, and socio-economic conditions.

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